

CLAIMS

What is claimed is:

1. An actuator assembly comprising:
  - a. an actuator support;
  - b. a fixed comb connected to the actuator support and having a plurality of fixed teeth extending in a first direction;
  - c. a member frame flexibly connected to the actuator support and having a first fulcrum axis;
  - d. a movable comb connected to the member frame and having a plurality of movable teeth extending in the first direction, wherein the fixed and movable teeth are arranged interdigitally from a perspective perpendicular to the first direction and the first fulcrum axis; and
  - e. an actuated member connected to the member frame and movable with respect to the member frame along a second fulcrum axis.
2. The actuator assembly of claim 1, wherein the second fulcrum axis is perpendicular to the first fulcrum axis.
3. The actuator assembly of claim 1, further comprising:
  - a. a frame comb rigidly connected to the member frame and having a plurality of frame-comb teeth extending in a second direction different from the first direction; and
  - b. a member comb rigidly connected to the member and having a plurality of member teeth extending in

- the second direction;
- c. wherein the frame-comb teeth and the member teeth are arranged interdigitally from the perspective perpendicular to the first direction and the first fulcrum axis.
4. The actuator assembly of claim 3, wherein the second direction is perpendicular to the first direction.
5. The actuator assembly of claim 3, further comprising a hinge connecting the member frame to the actuator support, wherein the hinge includes a first portion electrically connected to the frame comb and a second portion electrically connected to the member teeth, and wherein the first portion is electrically insulated from the second portion.
6. The actuator assembly of claim 1, further comprising a hinge connecting the member frame to the actuator support.
7. The actuator assembly of claim 6, wherein the hinge comprises a flexible member.
8. The actuator support of claim 1, further comprising:
- a. a second fixed comb rigidly connected to the actuator support and having a second plurality of fixed teeth extending in the first direction; and
  - b. a second movable comb rigidly connected to the member frame and having a second plurality of movable teeth extending in the first direction;

wherein the second plurality of fixed teeth and the second plurality of movable teeth are arranged interdigitally from the perspective perpendicular to the first direction and the first fulcrum axis.

9. The actuator assembly of claim 8, further comprising:
  - a. a second frame comb rigidly connected to the member frame and having a second plurality of frame-comb teeth extending in the second direction; and
  - b. a second member comb rigidly connected to the member and having a second plurality of member teeth extending in the second direction;
  - c. wherein the second plurality of frame-comb teeth and the second plurality of member teeth are arranged interdigitally from the perspective perpendicular to the first direction and the first fulcrum axis.
10. The actuator assembly of claim 1, wherein the member comprises a mirror surface.
11. The actuator assembly of claim 10, wherein the mirror surface comprises gold.
12. The actuator assembly of claim 10, wherein the actuator assembly occupies a first area in a plane defined by the first fulcrum axis and the second fulcrum axis, and wherein the mirror surface occupies a second area at least one fourth the area of the

first area.

13. The actuator assembly of claim 1, wherein the fixed comb comprises a semiconductor.
14. The actuator assembly of claim 1, further comprising a hinge connecting the member frame to the actuator support, wherein the hinge is thinner than the fixed comb in a second direction perpendicular to the first and second axes.
15. The actuator assembly of claim 14, wherein the hinge comprises two electrically conductive portions separated by an electrically insulating portion.
16. The actuator assembly of claim 14, wherein the hinge is serpentine.
17. The actuator of claim 1, wherein the fixed teeth are of varying length.
18. The actuator of claim 1, wherein the movable teeth are of varying length.
19. The actuator assembly of claim 1, wherein the first fulcrum axis bisects the actuated member.
20. The actuator assembly of claim 19, wherein the second fulcrum axis bisects the actuated member.
21. The actuator assembly of claim 1, further comprising a

- torsional hinge connected between the actuator support and the fixed comb.
22. The actuator assembly of claim 1, further comprising an integrated circuit bonded to the actuator support and adapted to supply control voltages to at least one of the fixed and movable combs.
23. An actuator assembly comprising:
- a. an actuator support;
  - b. a first comb means connected to the actuator support;
  - c. an actuated member flexibly connected to the actuator support;
  - d. a second comb means connected to the actuated member and adapted to move relative to the first comb means to position the actuated member;
  - e. wherein the actuated member rotates in a first dimension along a first fulcrum axis with respect to the actuator support; and
  - f. wherein the actuated member rotates in a second dimension along a second fulcrum axis with respect to the actuator support.
24. The actuator assembly of claim 23, wherein the actuated member is adapted to move in a third dimension with respect to the actuator support.
25. The assembly of claim 23, further comprising a mirror disposed on the actuated member.

26. An actuator comprising:

- a. an actuator support;
- b. a first set of teeth connected to the actuator support and extending in parallel;
- c. a second set of teeth connected to the actuator support and extending in parallel;
- d. an actuated member connected to the actuator support;
- e. a third set of teeth connected to the actuated member, wherein the teeth of the third set of teeth extend in parallel with the teeth of the first set of teeth, and wherein the first and third sets of teeth are arranged interdigitally from at least one perspective;
- f. a fourth set of teeth connected to the actuated member, wherein the teeth of the fourth set of teeth extend in parallel with the teeth of the second set of teeth, wherein the second and fourth sets of teeth are arranged interdigitally from the at least one perspective, and wherein the teeth of the first and second sets are not parallel.

27. The actuator of claim 26, wherein applying a first voltage difference between the first set of teeth and the third set of teeth moves the actuated member along a first rotational axis relative to the actuator support, and wherein applying a second voltage difference between the second set of teeth and the fourth set of teeth moves the actuated member along a second rotational axis relative to the actuator

support.

28. The actuator of claim 27, wherein the first rotational axis is perpendicular to the second rotational axis.
29. The actuator of claim 27, wherein the first and third sets of teeth are curved.
30. An actuator comprising:
  - a. an actuator support;
  - b. an actuated member movably connected to the actuator support;
  - c. a first set of interdigitated combs adapted to pivot the actuated member relative to the actuator support along a first fulcrum axis in response to a first applied voltage; and
  - d. a second set of interdigitated combs adapted to move the actuated member relative to the actuator support along a second fulcrum axis in response to a second applied voltage.
31. The actuator of claim 30, wherein the actuated member is adapted to move relative to the actuator support in a plane parallel to the first and second fulcrum axes.
32. The actuator of claim 31, wherein the actuated member pivots in the plane.
33. The actuator of claim 30, wherein the actuated member is adapted to simultaneously move translationally and rotationally relative to the actuator support.

34. The actuator of claim 33, wherein the actuated member is adapted to simultaneously move relative to the actuator support translationally in two directions and rotationally.
35. A method of forming MEMS structures in first and second material layers separated by a third material layer, the method comprising:
- a. forming a first mask on the first material layer, leaving exposed portions of the first material layer;
  - b. etching the first material layer in the exposed portions of the first material layer down to the third material layer;
  - c. bonding the first material layer to a first side of a wafer;
  - d. grinding and polishing the second material layer to a second-material-layer;
  - e. forming a second mask on the second silicon layer, leaving exposed portions of the second material layer; and
  - f. etching the second material layer in the exposed portions of the second material layer down to the third material layer.
36. The method of claim 35, further comprising etching the third material layer.
37. The method of claim 35, further comprising, before forming the first mask, patterning and etching the



first material layer to a first depth less than the thickness of the first material layer to define a first pattern.

38. The method of claim 35, further comprising, before forming the second mask, patterning and etching the second material layer to a first depth less than the layer thickness to define a first pattern.
39. The method of claim 35, wherein the first material layer is a first-material-layer thickness substantially equal to the second-material-layer thickness.
40. The method of claim 35, wherein the first and second masks comprise an insulator.
41. The method of claim 35, wherein the wafer comprises silicon.
42. A photolithographic process sequence for manufacturing MEMS structures from a first material layer of a first-material-layer thickness disposed over and in contact with a second material layer, the sequence comprising:
- forming a mask over the first material layer, wherein the mask leaves portions of the first material layer exposed;
  - etching the first material layer in the exposed portions to a first depth less than the first-material-layer thickness, wherein the masked

- portions form a raised pattern defined by recessed areas formed in the exposed portions;
- c. removing at least a portion of the mask, leaving at least a portion of the raised pattern and the recessed areas exposed; and
  - d. etching the exposed raised pattern and recessed areas of the first material layer until the second material layer is exposed in the recessed areas, leaving the pattern affixed to the second material layer.
43. The method of claim 42, wherein the pattern comprises first and second portions and wherein forming the mask comprises:
- a. forming a first sub-mask defining the first portion of the pattern; and
  - b. forming a second sub-mask defining the second portion of the pattern.
44. The method of claim 42, wherein removing at least a portion of the mask comprises removing the second sub-mask.
45. The method of claim 44, wherein the second sub-mask comprises photoresist.
46. The method of claim 42, further adapted to manufacture a second collection of MEMS structures from a third material layer of a third-material-layer thickness, the sequence further comprising:
- a. forming a second mask over the third material

- layer, wherein the second mask leaves portions of the third material layer exposed;
- b. etching the third material layer in the exposed portions of the third material layer to a second depth less than the third-material-layer thickness, wherein the masked portions of the third material layer form a second raised pattern defined by recessed areas formed in the exposed portions of the third material layer;
  - c. removing at least a portion of the second mask, leaving at least a portion of the second raised pattern and the recessed areas in the third material layer exposed; and
  - d. etching the exposed second raised pattern and recessed areas in the third material layer to remove the material in the recessed areas of the third material layer.
47. The method of claim 46, wherein substantially all of the material in the recessed areas of the third material layer is removed.
48. The method of claim 46, wherein the second material layer is disposed between the first material layer and the third material layer.
49. A photolithographic method of patterning a first material layer over a second material layer, the first material layer being of a thickness and having a first surface in contact with the second material layer and a second surface, the method comprising:

- a. forming a mask over the second surface of the first material layer, wherein the mask leaves portions of the second surface exposed;
  - b. etching the first material layer in the exposed portions to a first depth less than the thickness of the first material layer, wherein the masked portions form a raised pattern defined by recessed areas formed in the exposed portions;
  - c. removing the mask, leaving the raised pattern and the recessed areas exposed; and
  - d. etching the raised pattern and recessed areas of the first material layer until the second material layer is exposed in the recessed areas, leaving the pattern affixed to the second material layer.
50. The method of claim 49, wherein the first material layer comprises a semiconductor.
  51. The method of claim 50, wherein the second material layer comprises an insulator.
  52. The method of claim 49, wherein the first material layer comprises a semiconductor, and wherein the second material layer comprises an insulator.
  53. The method of claim 49, wherein the mask comprises a semiconductor.
  54. The method of claim 49, wherein at least one of the etchings are accomplished using a reactive ion etch

process.

55. A micro-machining method for patterning a first material layer over a second material layer, the first material layer being of a thickness and having a first surface in contact with the second material layer and a second surface, the method comprising:

- a. forming a first mask over the second surface of the first material layer, wherein the first mask leaves portions of the second surface exposed;
- b. etching the first material layer in the exposed portions to a first depth less than the thickness of the first material layer, wherein the masked portions form a raised pattern defined by recessed areas formed in the exposed portions;
- c. forming a second mask over a first portion of the raised pattern, leaving a second portion of the raised pattern and the recessed areas exposed; and
- d. etching the second portion of the raised pattern and recessed areas of the first material layer until the second material layer is exposed in the recessed areas, leaving the pattern affixed to the second material layer, wherein the second mask protects the first portion of the raised pattern from the etching of (d), leaving the second portion of the raised pattern thinner than the first portion of the raised pattern.

56. The method of claim 55, wherein the second mask comprises at least a portion of the first mask.

57. The method of claim 55, wherein the first mask comprises photoresist.
58. The method of claim 55, wherein the first material layer comprises a semiconductor and the second material layer comprises an insulator.
59. The method of claim 55, further comprising removing at least a portion of the second material layer.
60. A photolithographic method of patterning a first material layer disposed beneath a second material layer, the second material layer being of a thickness and having a first surface in contact with the first material layer and a second surface, the method comprising:
- forming a first mask over the second surface of the second material layer, wherein the first mask leaves portions of the second surface exposed;
  - etching the second material layer in the exposed portions down to the first material layer;
  - focusing a photolithographic image on the second surface of the second material layer;
  - adjusting the focus of the photolithographic image by an offset equal to the thickness of the second material layer; and
  - forming a second mask over the first material layer.
61. The method of claim 60, wherein the first material

layer is an insulator.

62. The method of claim 60, wherein the second material layer is a semiconductor layer.
63. The method of claim 60, wherein focusing the photolithographic image on the second surface of the second material layer takes place before forming the first mask.
64. The method of claim 60, further comprising etching the first material layer through the second mask.
65. The method of claim 64, wherein etching the first material layer exposes a third material layer.
66. The method of claim 65, wherein the etched first material layer forms a third mask, the method further comprising etching the third material layer through the third mask.
67. The method of claim 66, wherein etching the third material layer exposes a forth material layer.
68. The method of claim 60, wherein the second material layer comprises a plurality of sub-layers.
69. The method of claim 68, wherein at least one of the sub-layers comprises a semiconductor.
70. A photolithographic process sequence for manufacturing

MEMS structures from a first material layer disposed over a second material layer, the sequence comprising:

- a. forming a first mask over the second material layer, wherein the first mask leaves portions of the second material layer exposed;
- b. etching through the second material layer in the exposed portions;
- c. forming a second mask over the first material layer through the exposed portions of the second material layer, wherein the second mask leaves portion of the first material layer exposed; and
- d. etching the exposed portion of the first material layer.

71. The process sequence of claim 70, wherein a third material layer is disposed between the first material layer and the third material layer, and wherein the second mask comprises portions of the third material layer.

72. The process sequence of claim 71, wherein the third material layer comprises silicon dioxide.

73. The process sequence of claim 72, wherein etching the exposed portions of the first material layer removes less than all of the exposed portion of the first material layer; wherein the portions exposed by the second mask form a raised pattern defined by recessed areas formed in the exposed portions.

74. The process sequence of claim 73, further comprising:



- a. forming a third mask over a first portion of the raised pattern, leaving a second portion of the raised pattern and the recessed areas exposed; and
- b. etching the second portion of the raised pattern and recessed areas of the first material layer to remove substantially all of the first material layer in the recessed areas, leaving the pattern.

75. The process sequence of claim 70, wherein the first material layer comprises a semiconductor.